Negative and positive Goos-Hänchen shifts of partially coherent light fields

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The negative and positive Goos-Hänchen (GH) shifts in reflected light are revisited for a partial coherent light incident on a cavity. A three-level dilute gaseous atomic medium, which follows two-photon Raman transitions, is considered in a cavity. The anomalous (negative group index) and normal (positive group index) dispersions of the intracavity medium lead to negative and positive GH shifts, respectively. The effects of beam width, spatial coherence, and mode index of partial coherent light fields are studied on the negative and positive GH shifts. It is observed that the amplitude of negative and positive GH shifts are relatively large for a small range of beam width and for a small value of spatial coherence of partial coherent light beams. The amplitude of GH shifts becomes small for large beam width and spatial coherence of incident light. Further, the distortion in the reflected light field increases when the amplitude of the GH shifts increases and vice versa.

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I. INTRODUCTION

The longitudinal Goos-Hänchen (GH) shift refers to the lateral displacement of a light beam from its expected geometrical optics path. The existence of this lateral shift was observed experimentally by Goos and Hänchen in 1947 [1], when a light beam was totally reflected from the interface of two different media. Since then a lot of attention has emerged to study the lateral shift using different systems [2–9]. Furthermore, due to the fundamental nature of the lateral shift, there are certain interesting applications. For example, in optical heterodyne sensors GH shifts can be used to measure various quantities such as beam angle, refractive index, displacement, temperature, and film thickness [10]. The phenomenon of GH shift can also be used for the characterization of the permeability and permittivity of the materials [11] and in the development of near-field optical microscopy and lithography [12].

In addition, coherent control of the negative and positive GH shifts in the reflected light was investigated for the first time by Wang *et al.* in 2008 [13]. In this proposal, a two-level atomic medium was considered in a cavity and the control of negative and positive GH shift in the reflected light was investigated by modifying the susceptibility of the atomic medium with an external control field. Since then several proposals have been investigated using different atomic media inside a cavity [14–18]. In these investigations, a coherent light beam has been used to study the corresponding GH shifts in the reflected light without changing the structure of the medium. It is found that the negative and positive GH shifts are based on the negative and positive group index of the medium, respectively. To the best of our knowledge, in all the above theoretical investigations on the GH shifts a completely coherent light is considered only. These investigations show that coherence plays an important role to study the GH shift. Now a question arises whether the GH shift is affected by the spatial coherence or not. The answer to this question was partially given by Simon and Tamir in 1989 [19], where a multilayer structure was considered and investigated. It was found that the GH shift could not be affected by the coherence of light. Similarly, a theory of GH shift has been presented by Aiello and Woerdman for partially coherent light and it is revealed that the spatial coherence has no effect on GH shift [20]. Recently, the effect of spatial coherence on GH shift was studied experimentally, with the conclusion that the spatial coherence does not affect the GH shift [21,22].

However, in some studies [23,24], it was investigated that the GH shift of the reflected light beam depends on the spatial coherence. The result of these investigations [23,24] has a clear contradiction with Refs. [19–21]. More recently, this contradiction is resolved by Zubairy and coworkers by considering a partial coherent light beam in a total internal reflection [25]. In this proposal, an expression is developed for the GH shift of a partial coherent light beam in terms of mode expansion. They demonstrated that the GH shift has a strong dependence on spatial coherence and beam width. The results of this investigation [25] clearly explain the contradiction between Refs. [23,24] and Refs. [19–21].

In this article, we proceed with the idea of partial coherent light beam [25] to both negative and positive GH shifts in the reflected light. The partial coherent light is incident on a cavity containing three-level atoms as the intracavity medium, which exhibits a Raman gain process. The proposed atomic system inside the cavity is used for gain-assisted superluminal light propagation [26] and also for the control of the GH shift [15]. Following the similar atomic configuration, here, we study the control of negative and positive GH shifts in the reflected light beam, corresponding to the negative and positive group index of the atomic medium, respectively, using a partial coherent light beam. We study the effect of partial coherence, beam width, and mode index of partial coherent light on the negative and positive GH shifts in the reflected light beam. Further, we also study the distortion in the GH shift in the reflected light beam for different modes of partial coherent light field.

II. MODEL

A. Fundamental concept

We follow the same approach used earlier in Ref. [25] and consider a partial coherent light field that incidents on a cavity,

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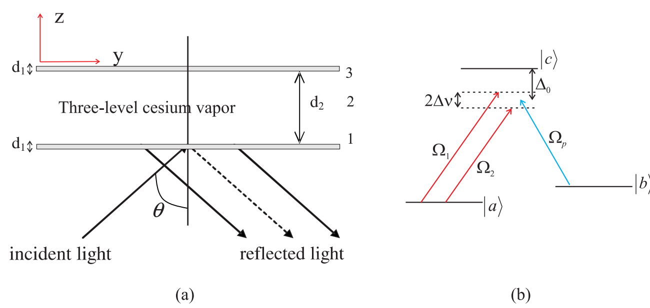

FIG. 1. (Color online) (a) The schematics of the light incident on a cavity (b) the energy-level configuration inside the cavity.

which contains a cesium atomic vapor cell. The incident partial coherent light beam makes an angle θ with respect to the z axis. Inside the cavity, each atom follows three-level atomic configuration with two-photon transition. Our proposed cavity consist of three layers: 1, 2, and 3, as shown in Fig. 1(a). The layers 1 and 3 are the walls of the cavity with thickness d_1 and permittivity ϵ_1; while layer 2 is the intracavity medium with thickness d_2 and permittivity ϵ_2. The permittivity ϵ_2 of the intracavity medium is directly related to the susceptibility of the medium via the relation $\epsilon_2 = 1 + \chi$ [14–18].

For an incident partial coherent light beam for mth mode [25], the electric field at $z = 0$ can therefore be written as

$$E_m^i(z,y) = \frac{1}{\sqrt{2\pi}} \int E_m\left(k_y - k_{y_0}\right) e^{i(k_z z + k_y y)} dk_y, \quad (1)$$

where

$$E_m\left(k_y - k_{y_0}\right) = \frac{1}{(2c\pi)^{1/4}} \times \frac{(-i)^m}{\sqrt{2^m m!}} \times e^{\frac{(k_y - k_{y0})^2}{4c}} \times H_m\left(\frac{\left(k_y - k_{y_0}\right)}{\sqrt{2c}}\right), \quad (2)$$

is the angular spectrum for partial coherent light beam, which can be calculated by considering a Gaussian Schell-model (GSM) beam. The normalized eigenfunctions of the GSM beams are given in Ref. [27] as

$$E_m(y) = (2c/\pi)^{1/4} \times \frac{1}{\sqrt{2^m m!}} H_m[y\sqrt{2c}]e^{-cy^2}. \quad (3)$$

The angular spectrum $E_m(k_y)$ can be calculated by taking Fourier transform of Eq. (3). Here, for the inclined incidence, $E_m(k_y)$ is replaced by $E_m(k_y - k_{y_0})$, where k_y is the y component of the wave vector $\mathbf{k}$ in our proposed cavity, $k_{y_0} = k\sin\theta$, and θ is the incident angle. In Eqs. (2) and (3), H_m is the Hermite polynomials and c can be calculated from the eigenvalues $\beta_m = A^2[\pi/(a+b+c)]^{1/2}[b/(a+b+c)]^m$ of the GSM beams with $a = (4w_s^2)^{-1}$, $b = (2w_g^2)^{-1}$, and $c = [a^2 + 2ab]^{1/2}$. Here, w_s and w_g are the half beam width and spectral coherence width of partial coherence fields, respectively. The value of c can now be obtained as $c = (q^2+4)^{1/2}/(4qw_s^2\sec^2\theta)$ by considering $w_s \to w_s\sec\theta$ and $w_g \to w_g\sec\theta$, where $q = w_g/w_s$ can measure the degree of coherence of the GSM beam.

The expression for the reflected partial coherent light beam for mth mode can therefore be written as [25]

$$E_m^r(y) = \frac{1}{\sqrt{2\pi}} \int r(k_y) E_m\left(k_y - k_{y_0}\right) e^{ik_y y} dk_y, \quad (4)$$

where $r(k_y)$ is the reflection coefficient of the stratified medium, which can be obtained using the characteristic matrix approach as has been calculated with detail in Ref. [14].

The exact expression for the GH shift has been derived [25] for the mth mode of the reflected field as

$$S_m^r = \frac{\int y\left|E_m^r(y)\right|^2 dy}{\int \left|E_m^r(y)\right|^2 dy}. \quad (5)$$

For the incident partial coherent light beam with different number of modes, the reflected light beam can be distorted. Therefore, it will be more valuable to study the distortion of partial coherent light beam for different number of modes. We define an explicit expression to measure the distortion $(\overline{w}_m/w_s)$, where $\overline{w}_m = (\beta_m)^{1/2}\cos\theta$ and the distortion in the reflected light beam for the mth mode can be measured using the normalized second moment of the electric field [16–18,28], i.e.,

$$\beta_m = 4\frac{\int \left(y - S_m^r\right)^2 \left|E_m^r(y)\right|^2 dy}{\int \left|E_m^r(y)\right|^2 dy}. \quad (6)$$

B. Atom-field interaction

We consider that each atom inside the cavity follows three-level Raman gain process [26] with energy levels $|a\rangle$, $|b\rangle$, and $|c\rangle$, see Fig. 1(b). Two far off-resonant fields E_1 and E_2 with correspond frequencies ν_1 and ν_2 are applied with the atoms. The atoms are initially prepared in level $|a\rangle$ and a probe field is applied between levels $|b\rangle$ and $|c\rangle$. The susceptibility of the atom-field interaction has been calculated in Refs. [15,26], i.e.,

$$\chi = \frac{M_1}{(\delta_p - \Delta\nu) + i\Gamma} + \frac{M_2}{(\delta_p + \Delta\nu) + i\Gamma}, \quad (7)$$

where

$$M_1 = N\frac{|\mu_{cb}|}{4\pi\hbar\epsilon_0}\frac{|\Omega_1|^2}{\Delta_0^2},$$

and

$$M_2 = N\frac{|\mu_{cb}|}{4\pi\hbar\epsilon_0}\frac{|\Omega_2|^2}{\Delta_0^2},$$

whereas $\delta_p = \nu_p - \nu_0$ and $\nu_0 = \nu_1 - \nu_{ca} + \nu_{cb}$, Γ is the Raman transition inverse lifetime.

III. RESULTS AND DISCUSSION

From an earlier study [15], the GH shifts in the reflected light beam has been investigated for a coherent light beam. The negative and positive GH shifts in the reflected light beam has been investigated corresponding to negative and positive group index of the atomic medium, respectively. In the following, we proceed with the study of the GH shifts in the reflected light [15,25] for partial coherent light beam incident on a cavity containing three-level atomic configuration. We study the control of the negative and positive GH shifts in the

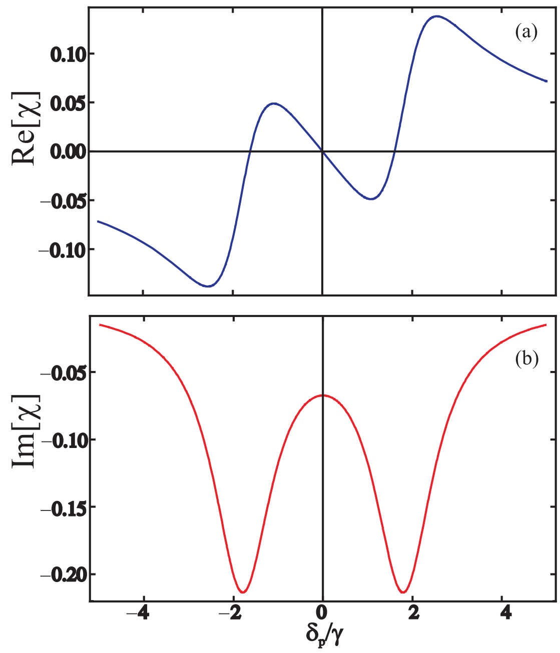

FIG. 2. (Color online) (a) Real and (b) imaginary parts of the optical susceptibility. The parameters are $\gamma = 1$MHZ, $\Gamma = 0.8\gamma$, $\Omega_1 = 2\gamma$, $\Omega_2 = 2\gamma$, $\Delta_1 = 5\gamma$, $\Delta_p = 4.9\gamma$, $\Delta\nu = 1.8\gamma$.

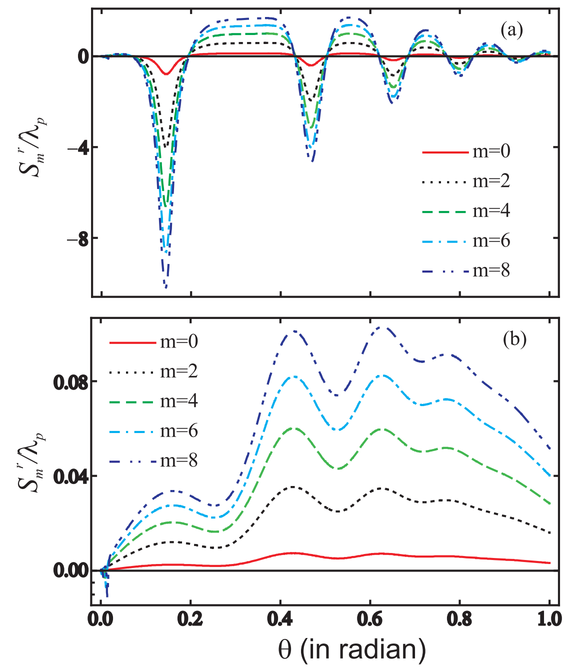

FIG. 3. (Color online) (a) Reflected S_m^r/λ_p GH shifts versus incident angle for anomalous dispersion, i.e., $\delta_p = 0$ and (b) normal dispersion $\delta_p = 1.8\gamma$, the other parameters are $\gamma = 1$ MHZ, $\Gamma = 0.8\gamma$, $\Omega_1 = \Omega_2 = 2\gamma$, $\Delta_1 = 5\gamma$, $\Delta_p = 4.9\gamma$, $\Delta\nu = 1.8\gamma$, $d_1 = 0.2$ μm, $d_2 = 5$ μm, $q = 0.1$, $\epsilon_1 = 2.22$, and $w_s = 100\lambda_p$.

reflected partial coherent light beam via probe field detuning. The real and imaginary parts of the optical susceptibility of the intracavity medium are presented versus probe field detuning δ_p in Fig. 2. The anomalous dispersion appears at and around $\delta_p = 0$ whereas normal dispersion appears at and around $\delta_p = 1.8\gamma$.

Initially, we study the behavior of GH shift for different number of modes of the partial coherent light beam incident on the cavity making an angle θ with the z axis. It is emphasized that each mode of the partial coherent light beam is perfectly coherent. In Fig. 3, we plot the GH shifts in the reflected light beam versus incident angle θ for anomalous and normal dispersion of the intracavity medium. We investigate negative and positive GH shifts for different choices of incident angle θ. The negative and positive GH shifts correspond to the negative and positive group index of the intracavity medium, as studied earlier for coherent light beam [14–18]. The amplitudes of the negative and positive GH shifts are different for different number of modes of the partial coherent light beam. We notice that the amplitude of the GH shift increases for some higher-order modes of partial coherent light, see Fig. 3.

To study the effect of different modes on the GH shift, we plot the negative and positive GH shift versus m for a fixed incident angle $\theta = 0.15$ radian. For anomalous dispersion of the intracavity medium, we plot the GH shift versus m, see Fig. 4(a). The plot shows that the negative GH shift increases to its maximum values around $m = 18$ and then decreases for further increasing the number of modes. Similarly, we plot the positive GH shift versus m see Fig. 4(b), which shows that the behavior of positive GH shift has the same tendency as that of negative GH shift. The amplitude of negative and positive GH shifts approaches to zero when $m \to \infty$. This is due to the fact that for any q, if $m \to \infty$, we have $S_\infty^r = 0$, since the effective width of partially coherent light tends to infinity [25].

The dependence of positive GH shift on spatial coherence q has been studied earlier [25] and investigated that the

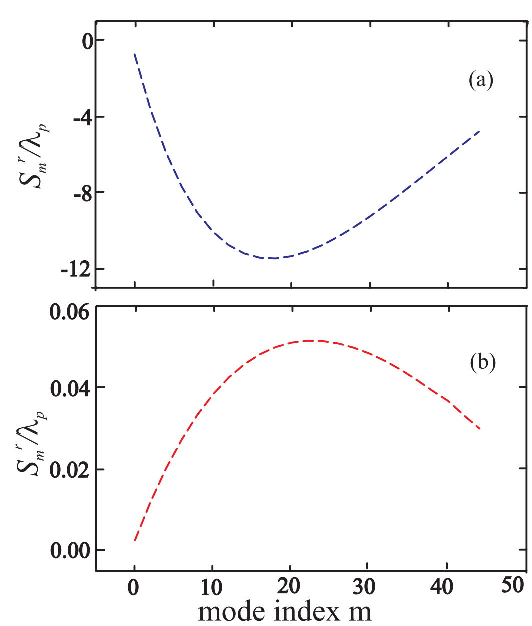

FIG. 4. (Color online) (a) Reflected S_m^r/λ_p GH shifts versus mode index m for anomalous dispersion i.e., $\delta_p = 0$, $w_s = 100\lambda_p$, and $\theta = 0.15$ radian and (b) for normal dispersion, i.e., $\delta_p = 1.8\gamma$, $w_s = 100\lambda_p$, and $\theta = 0.15$ radian. The other parameters remain the same as those in Fig. 3.

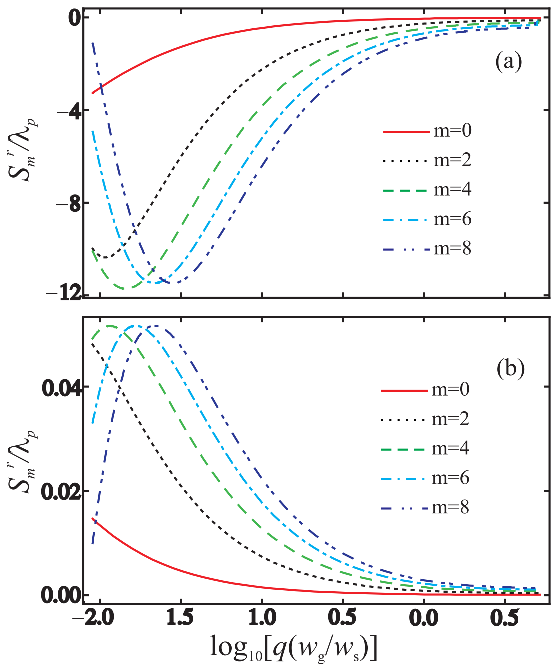

FIG. 5. (Color online) (a) Reflected S_m^r/λ_p GH shifts versus spatial coherence q for anomalous dispersion, i.e., $\delta_p = 0$, $w_s = 130\lambda_p$, and $\theta = 0.15$ radian and (b) for normal dispersion, i.e., $\delta_p = 1.8\gamma$, $w_s = 130\lambda_p$, and $\theta = 0.15$ radian. The other parameters remain the same as those in Fig. 3.

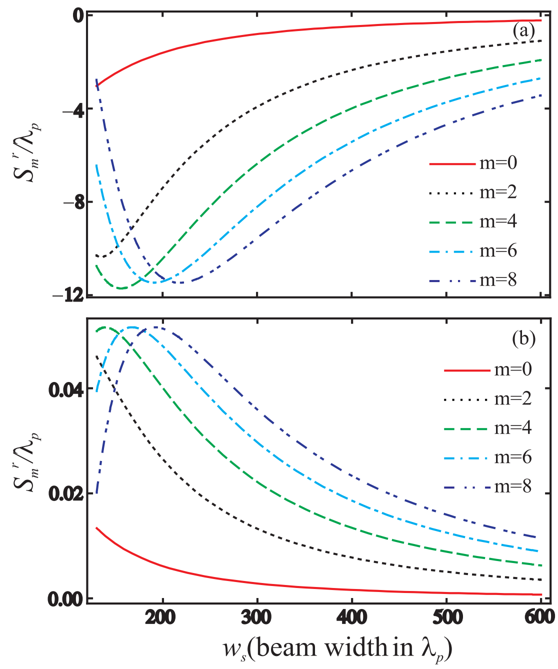

FIG. 6. (Color online) (a) Reflected S_m^r/λ_p GH shifts versus beam width w_s for anomalous dispersion, i.e., $\delta_p = 0$, $q = 0.01$, and $\theta = 0.15$ radian and (b) for normal dispersion, i.e., $\delta_p = 1.8\gamma$, $q = 0.01$, and $\theta = 0.15$ radian. The other parameters remain the same as those in Fig. 3.

amplitude of positive GH shift is high for small values of spatial coherence q. It is also studied that the amplitude of the positive GH shift decreases as the value of spatial coherence q increases. This is due to the fact that the light becomes more and more coherent when the values of the spatial coherence q increases and for small values of q a large number of modes are needed to represent the light field, i.e., the light becomes incoherent. In the following, we study the effect of spatial coherence on negative and positive GH shifts for different modes of partial coherent light beam in a slab system (cavity). For anomalous dispersion of the intracavity medium, i.e., $\delta_p = 0$, we plot the GH shifts in the reflected light versus spatial coherence $\log_{10}[q]$ for different modes at incident angle $\theta = 0.15$ radian. The anomalous dispersion (negative group index) of the intracavity medium leads to negative GH shifts in the reflected light beam, see Fig. 5(a). The amplitudes of the negative GH shifts are very high for small values of the spatial coherence and decreases gradually when q increases. Above a certain value of spatial coherence, the amplitude of the negative GH shifts remain almost constant. Then, we change the probe field detuning of the intracavity medium from $\delta_p = 0$ to $\delta_p = 1.8\gamma$. The anomalous dispersion converts to normal dispersion [15,26], which leads to a positive group index of the intracavity medium. We plot again the GH shifts in the reflected light beam versus spatial coherence $\log_{10}[q]$ for different modes of partial coherent light, see Fig. 5(b). By comparing Figs. 5(a) and 5(b), it is found that the behavior of positive GH varies as the same as that of negative GH shifts. Furthermore, the resonance condition in such a slab cavity disappears when the light becomes incoherent. For incoherent limit, i.e., $\log_{10}[q] = -2$, the negative and positive GH shifts decreases normally. It is noted that for spatial coherence $q \to 0$, the light becomes completely incoherent, which has an infinite number of modes ($m \to \infty$), which leads to $S_\infty^r \to 0$.

Next, we discuss the effect of the beam width of partial coherent light beam on the GH shift. Earlier, it has been noticed that the beam width of the Gaussian beam [16,18,29] and the partial coherent light beam [25] play an important role on the GH shift. When the beam width of the partial coherent light beam increases, the effect of partial coherence q on the GH shift decreases and vice versa. Following this idea we study the negative and positive GH shifts in the reflected beam of partial coherent light. First, we consider $\delta_p = 0$ for anomalous dispersion of the intracavity medium and plot the GH shift in the reflected beam versus beam width w_s of partial coherent light, see Fig. 6(a). For anomalous dispersion of the intracavity medium, i.e., negative group index of the medium, we investigate negative GH shifts for different number of modes of partial coherent light. The negative GH shifts in the reflected light increase with the beam width and reach a maximum value around $w_s \cong 160\lambda_p$. Then the GH shifts decrease with further increase in the beam width w_s of partial coherent light. The negative GH shifts in the reflected light are approximately equal to constant for further increase of beam width w_s of partial coherent light. For normal dispersion of the intracavity medium, i.e., $\delta_p = 1.8\gamma$, we again plot the GH shifts in the reflected light for different modes of partial coherent light versus beam width w_s, see Fig. 6(b). We investigate positive GH shifts in the reflected light for different modes of partial coherent light. This time we observe the same kind of behavior as we previously observed for negative GH shifts in Fig. 6(a). Here, from Figs. 5 and 6, we can conclude

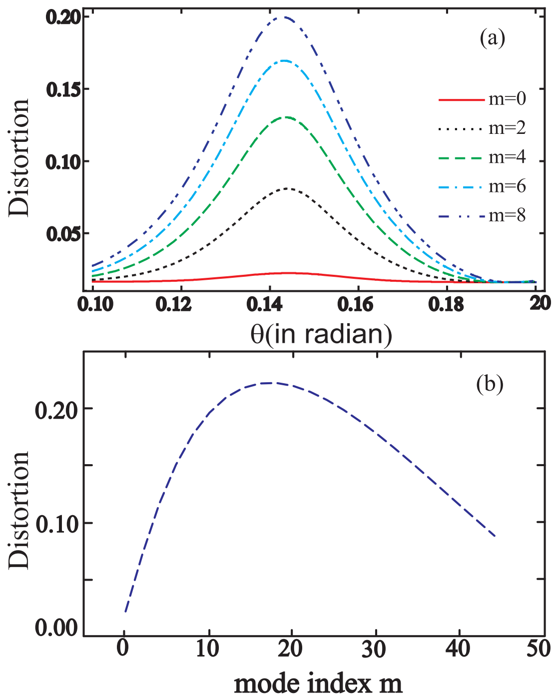

FIG. 7. (Color online) (a) Distortion $\overline{w}_m/w_s$ versus incident angle θ for anomalous dispersion, i.e., $\delta_p = 0, q = 0.1$, and $w_s = 100\lambda_p$ and (b) Distortion $\overline{w}_m/w_s$ versus mode index m for anomalous dispersion i.e., $\delta_p = 0$, $q = 0.1$, and $w_s = 100\lambda_p$. The other parameters remain the same as those in Fig. 3.

that the role of w_s on S_m^r for a small q remains the same as the role of q on S_m^r for a small w_s. Similarly, the effect of large q and large w_s on S_m^r in both negative and positive GH shifts in the reflected light remains the same, cf. Figs. 5 and 6. Therefore, the beam width w_s and spatial coherence q have the same role on the negative and positive GH shifts in the reflected beam. In Fig. 4, it is found that the amplitudes of negative and positive GH shifts in the reflected light dramatically increases first, but then decreases if the number of modes of partial coherent light further increases.

Now, we illustrate the distortion in the reflected light beam. To measure the distortion in the reflected light for the GH shift, we use Eq. (6) and plot the ratio $\overline{w}_m/w_s$ versus incident angle θ for anomalous dispersion of different modes of partial coherent light. We also plot the ratio $\overline{w}_m/w_s$ verses mode index m for partial coherent light beam. The plot in Fig. 7(a) shows that the distortion in the reflected light beam increases when the mode index m increases. Following this observation, we plot the ratio $\overline{w}_m/w_s$ versus mode index m for a fixed incident angle $\theta = 0.15$ radian. The plot shows that initially the distortion increases and reaches to a maximum value, then it decreases for higher-order values, see Fig. 7(b). By comparing Figs. 4(a) and 7(b), it is concluded that the distortion in the reflected light increases when the amplitude of the GH shift increases and vice versa.

IV. CONCLUSION

In conclusion, we considered a three-level gain-assisted model inside a cavity and studied the GH shifts for a partial coherent light beam incident into such a cavity with an angle θ to the z axis. The anomalous and normal dispersions of intracavity medium lead to negative and positive GH shifts, respectively. The effects of beam width, spatial coherence, and mode index of partial coherent light on the GH shifts are studied. We find that both the amplitudes of negative and positive GH shifts in the reflected light dramatically increase first, but then decrease as the mode index m of partial coherent light goes larger. Furthermore, the distortion in the reflected light beam is studied and investigated, which increases when the amplitude of GH shift is high. In most of practical implementation, the coherent light sources are usually not available. For example, the x-ray beams are partially coherent [30], and the observed GH shift using x-ray beams is reported in Ref. [31]. Our results on the negative and positive GH shifts may provide a direction on the applications for partial coherent light sources.

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